CONF-831171--15

NOTE: This is a draft of a paper

CONF-831171--15

DE84 003308

CHARACTERIZATION OF THE TEXTOR PLASMA EDGE USING DEPOSITION PROBE TECHNIQUES

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MASTER

October 1983

CHARACTERIZATION OF THE TEXTOR PLASMA EDGE USING DEPOSITION PROBE TECHNIQUES*

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Carbon and single crystal silicon passive deposition probes were used to measure the characteristics of the plasma edge region of the TEXTOR tokamak. Analysis of the probes was done by Rutherford backscattering for impurities and nuclear reaction analysis and elastic recoil detection for hydrogen isotopes. Plasma fluxes and energies in the edge were measured using probe techniques. The principal impurities in the plasma edge were determined and their behavior as a function of time and position was measured. Measurements were also made of in situ erosion rates. The results are compared with independent measurements of other plasma parameters to study possible impurity introduction mechanisms. This work represents the first deposition probe measurements made in the plasma edge of TEXTOR.

I. INTRODUCTION

Deposition probe techniques have proven to be an effective method of studying the plasma edge region of magnetic confinement fusion devices.[1] In the present work the application of these techniques to characterization of the scrapeoff layer of the TEXTOR tokamak at KFA Juelich, FRG, is described. TEXTOR is a moderate size tokamak (major radius = 1.75 m) that

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*Research sponsored by the U. S. Department of Energy under Contract W-7405-eng-26 with Union Carbide Corporation.

is constructed of Inconel and contains an Inconel liner that acts as the first wall and can be heated electrically to 600°C. For the measurements reported here, the wall temperature was 300°C and stainless steel limiters were used. Radio assisted glow (RG) discharge cleaning[2] was used effectively to condition the vacuum vessel after an opening or before an experimental sequence of shots. Typical operating parameters during the present investigations were toroidal field, $B_t = 2$ Tesla, toroidal current, $I_p =$ 300 kA, and average electron density, $\bar{n}_e = 2 \times 10^{13}/\text{cm}^3$, but currents of 500 kA and densities of $4 \times 10^{13}/\text{cm}^3$ have been achieved.[3]

II. EXPERIMENTAL PROCEDURE

Deposition probe exposures were made along a major radius in the horizontal midplane of the tokamak between toroidal field coils # 7 and 8. This sector was adjacent to the limiter sector and the probe was located only 19° in the ion drift direction from the main outside limiter. The insertion and positioning of the probe were micro-processor controlled with complete electrical isolation using optical couplers between the tokamak and the diagnostic area. Exposures were made as functions of radius and direction. Time resolved measurements were made by electrically rotating a cylindrical sample behind a fixed slot. Two collector materials were employed, carbon (Papyex) strips for hydrogen and deuterium, and single crystal silicon for impurities. All exposures were made with the probe at floating potential. Sample temperature was monitored throughout with a remote reading thermocouple gauge. The maximum sample temperature observed was 270°C. After exposure the samples were transferred in air to an accelerator facility for analysis. Rutherford ion backscattering (RBS) with 2.0 MeV ^{4}He was used for impurity detection,[4] while elastic recoil detection (ERD) with 1.75 MeV ^{4}He at 30°[5] and nuclear reaction analysis (NRA) with the D(^{3}He,p)^{4}He reaction[4] were used for the hydrogen isotopes. Channeling techniques[6] were applied to enhance the sensitivity of the RBS results.

III. RESULTS AND DISCUSSION

A. Hydrogen and Deuterium

The radial variation of retained hydrogen and deuterium was measured as a function of distance outside the limiter for a large number of discharges. In all cases, for both the ion and electron directions, the deposition was essentially uniform over the observed region from $r - r_\ell$ = 2.7 to 7.3 cm. Retained fluences integrated over a single discharge for both hydrogen and deuterium were 3.7 x 10^{15}/cm^2 disch., with variations of up to a factor of two observed between discharges.

Time resolved D deposition rates were measured with a time resolution of ±150 ms using the rotating system described in Section II. The results are plotted in Fig. 1 along with independent measurements of the loop voltage, V, plasma current, I_p, and average electron density $\bar{n}_e$ for exposures to two different sets of D discharges. The upper D curve presents the flux deposited on a carbon probe exposed in the ion direction to three discharges that are typified by the voltage, current and density traces above it. These discharges are long and quiet, lasting 2.5 s and showing minimal disruptive activity as demonstrated by the constant loop voltage. Notice that after the initial peak, which has been observed during startup in the scrapeoff layer of many machines,[1,7] the deposited flux is low and steady, indicating a stable, centered plasma that is not interacting strongly with the limiters. The minimal interaction with the limiters during this type of discharge is confirmed by direct video observations.[8] These discharges also show the lowest levels of metallic impurities in the plasma edge.[9]

The lower half of Fig. 1 shows the deuterium retained on samples exposed in the electron direction to five discharges, two of them as just described, and three as typified by the lower set of voltage and current curves. Here the discharge becomes disruptive, as evidenced by spikes in the loop voltage, and terminates in less than one second. The disruptive behavior results in increased D flux to the probe from 0.5 to 1 second. Substantially higher metallic impurity levels are also observed for this type of discharge.[9]

B. Plasma Fluxes and Energies

A number of exposures were made to determine the trapping or saturation behavior of hydrogen and deuterium in the probe material. Such data can be used to estimate the flux and energy of the incident particles.[10,11] Deposited quantities were essentially constant at radial positions from 3 to 7 cm outside the limiter radius. Trapping curves for data at these radii in the ion drift direction gave similar results. The incident deuterium fluence and energy were found to be $1 - 1.5 \times 10^{16}/\text{cm}^2$ disch. with a Maxwellian energy distribution with kT = 100 eV. Substantial uncertainty exists in these results because of shot to shot variations, the time integrated nature of the data, and possible temperature effects in the samples.

The fluence and energy of hydrogen and deuterium were also estimated using damage to the single crystal silicon samples that were used for impurity collection. Such damage is representative of the incident particle flux and energy[12] and can be evaluated in a manner parallel to that used for deuterium trapping data. Only curves for monoenergetic normal incidence were available,[12] and these resulted in values for the incident fluence at $r - r_\ell = 4$ cm of ~ $5 \times 10^{15}/\text{cm}^2$ disch. at energies from 150 - 300 eV. These energies are somewhat higher than the mean energy found in the Maxwellian case, ~150 eV, while the fluxes are comparable since the Maxwellian case implies an isotropic velocity distribution and the monoenergetic case is normal incidence.

A probe system using thermal desorption techniques to measure hydrogen or deuterium fluxes to carbon probes has recently become operational on TEXTOR. Preliminary results from this system give retained amounts comparable to those obtained here, namely a few x $10^{15}/\text{cm}^2$ disch.[13] Energies have not yet been determined from this system.

C. Impurities

Initial results of the impurity investigations on TEXTOR have recently been presented,[9] but are summarized here for completeness. The principal impurities in the edge were found to be carbon, oxygen, iron, nickel, and chromium. Fluxes deposited on the probe were on the order of $10^{15}/\text{cm}^2$ s for carbon and oxygen, and 1-5 x $10^{14}/\text{cm}^2$ s for the combined total of the transition metals. Iron was the dominant metal, showing an approximate ratio of 4:2:1 to nickel and chromium. The radial dependence was found to be relatively flat from 3 to 5.5 cm outside the limiter radius with a peaking, especially of the metallic impurities, near the liner. This peaking effect has since been investigated more thoroughly and the results are shown in Fig. 2. Here the deposited metal fluence in the positive ion direction is plotted vs. distance beyond the limiter, $r - r_\ell$, for three discharges in hydrogen and three in deuterium. The uniform deposition out to $r - r_\ell$ = 5.5 cm is evident and is followed by a sharp increase from 5.5 to 7.5 cm. This increase shows an e-folding length of 1.2 cm and is believed to be due to influx of metallic neutrals from the liner which is located at $r - r_\ell \approx$ 10 cm. Such an e-folding length would dictate electron temperature and density of ~10 eV and ~2 x $10^{11}/cm^3$ or equivalent in this region.[14] The possibility that the shape of these profiles was due to competing erosion and deposition processes[15] was considered, but was ruled out by in situ erosion measurements that place a limit of $10^{14}/cm^2$ s on erosion at these radii (see III D) that is too small to account for the observed variations. It should also be noted that the deposition rates of Fig. 2 are about a factor of two higher in deuterium than in hydrogen plasmas. This is an indication that sputtering by plasma particles may be a significant metallic impurity introduction mechanism.

D. In Situ Erosion

Measurements were made of the in situ erosion rate of a 2.5 nm gold film deposited on a polished silicon substrate. The film thickness was measured before and after exposure to the plasma using RBS. Details of the technique have been published previously.[16] Erosion rates in TEXTOR for samples perpendicular to the magnetic field in the ion drift direction were close to the limits of detection in both hydrogen and deuterium plasmas, making accurate measurements difficult. However the average erosion rate for radii between 3 and 7 cm behind the limiter was found to be ~5 x 10^{13} atoms/cm^2 s, and an upper limit on erosion of $10^{14}/cm^2$ s during normal discharges can be assigned. Significant variations with radius were not observable.

IV. CONCLUSION

TEXTOR is capable of 2.5 s limiter discharges with central electron and ion temperatures of 1.3 and 0.8 keV respectively.[3] Time resolved deposition probe results for these discharges showed, after startup, a stable centered plasma with a minimum of impurities in the plasma edge. Shorter discharges showed greater plasma fluxes in the edge as well as higher impurity levels.

Average deuterium flux and energy at $r - r_\ell = 5$ cm were determined from trapping data to be $\sim 10^{16}/\mathrm{cm}^2$ s at a temperature of 100 eV, in reasonable agreement with similar estimates based on silicon damage rates. The principal impurities in the scrapeoff layer were found to be O, C, Fe, Ni, and Cr and their approximate fluxes were determined. Iron was the dominant metal in the edge, indicating that most of the metallic impurities originated from the stainless steel limiters, rather than from the Inconel liner. Relative impurity levels in H and D plasmas suggest that sputtering by plasma particles plays a role in impurity introduction.

In situ erosion measurements were made that place a limit of $10^{14}/\mathrm{cm}^2$ s on erosion at $r - r_\ell = 5$ cm.

Radial profiles for both plasma and impurities were found to be flat or slightly concave in the region of 3 to 5.5 cm outside the limiter. A sharp increase in metallic impurities having a characteristic length of 1.2 cm was observed from 5.5 to 7 cm outside the limiter radius and is ascribed to the ionization of neutral metal atoms entering the plasma from the liner. A strong increase in plasma and impurity fluxes approaching the plasma was not observed. It is anticipated that measurements made closer to the limiter radius would show such an increase. Thus the present observations suggest a region from 3 to 5 cm outside the limiter where impurities from the plasma and from the liner meet and form a minimum in circulating flux.

In summary, passive deposition probe techniques, in combination with accelerator based analysis, have been applied successfully in the TEXTOR tokamak to determine plasma edge parameters.

ACKNOWLEDGEMENT

The author is extremely grateful to all the members of the IPP, KFA Juelich, for the opportunity to work with them and for their help and cooperation during these investigations, and especially to H. Conrads, W. Hofer and K. Tschersich for coordinating his visit. Thanks are also due to DOE for making the assignment possible.

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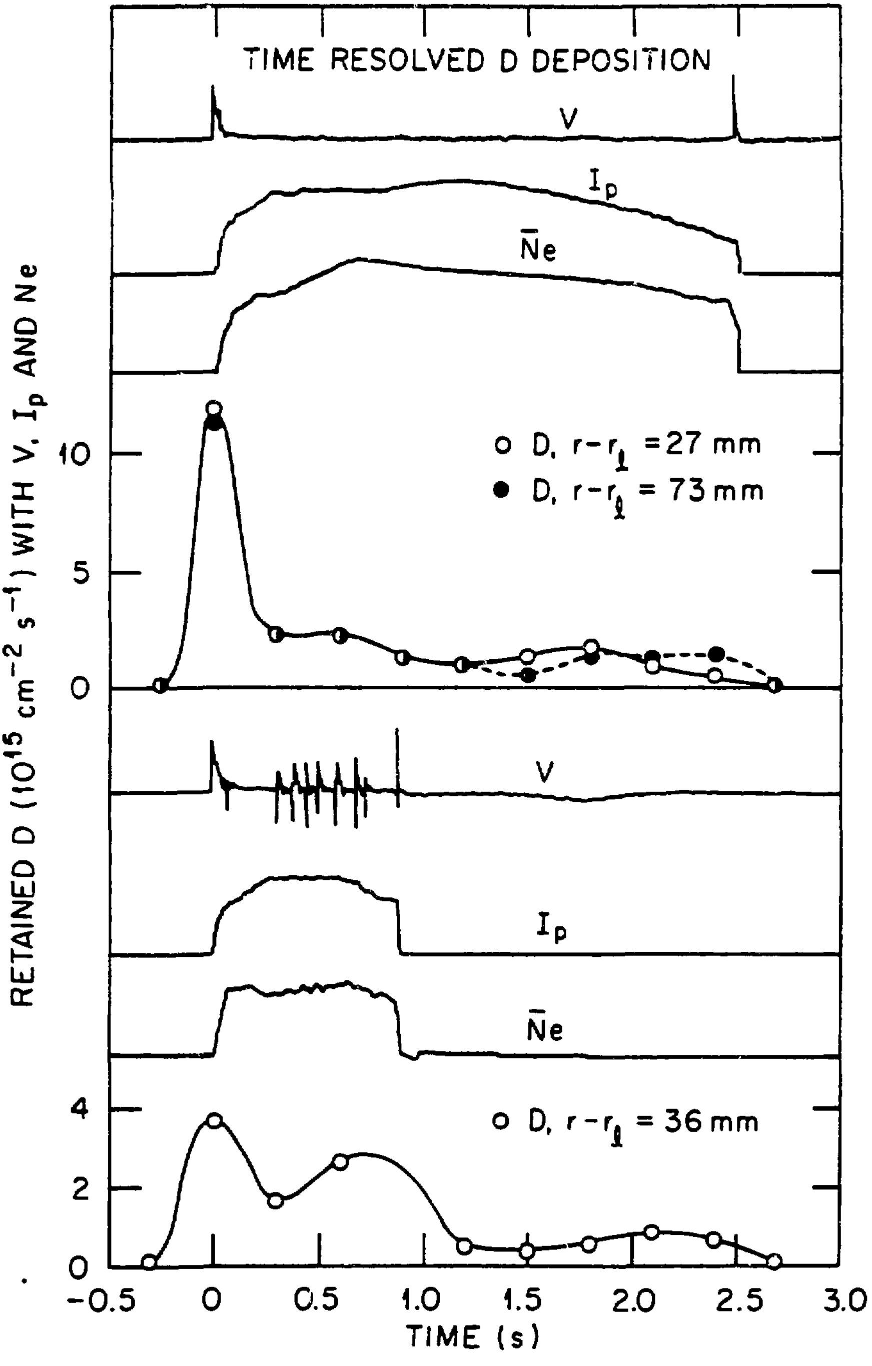
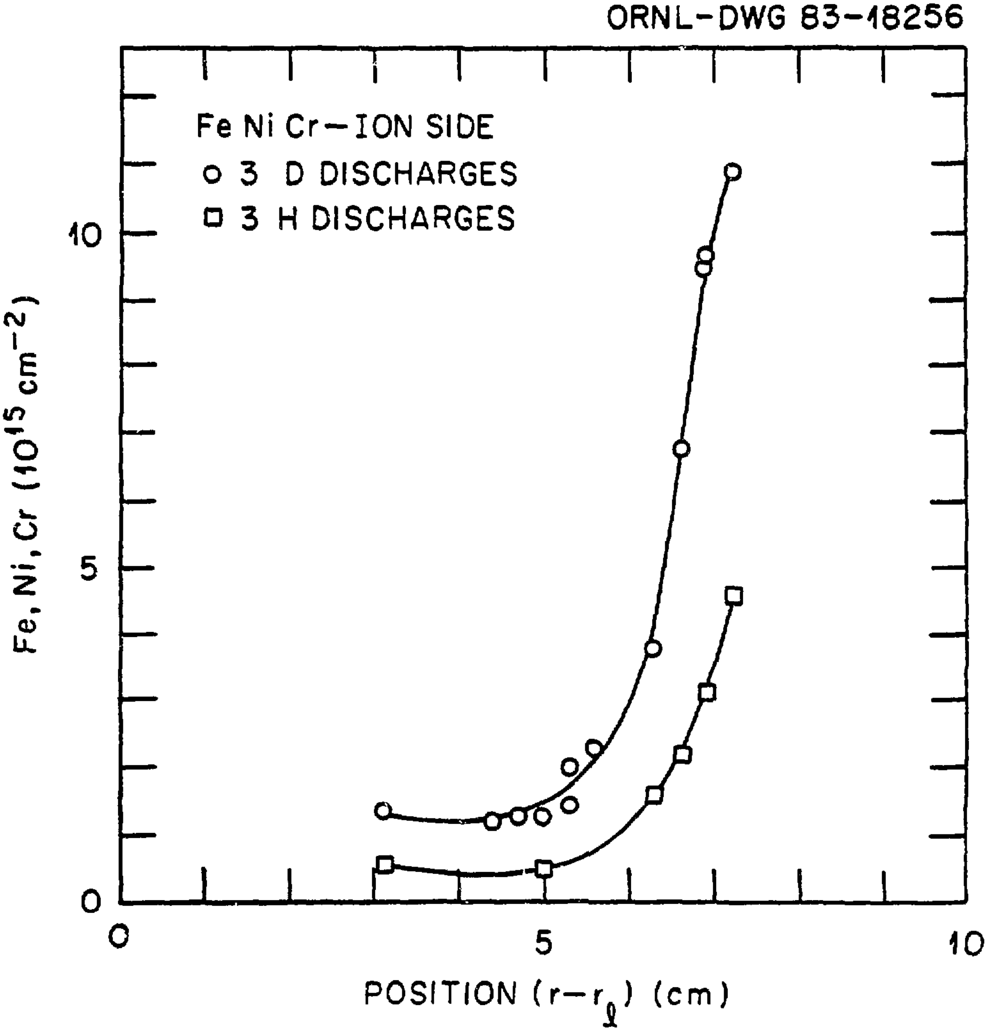
FIGURE CAPTIONS

Fig. 1. Time resolved D retention rate is compared with loop voltage, V, plasma current, I_p and average electron density, $\bar{n}_e$ for two different discharge types in TEXTOR.

Fig. 2. Retained metal (Fe, Ni, Cr) fluence vs radial position outside the limiter for 3 hydrogen and 3 deuterium discharges in TEXTOR.

ORNL-DWG 83-18253




ORNL-DWG 83-18256
Fe Ni Cr—ION SIDE
○ 3 D DISCHARGES
□ 3 H DISCHARGES
Fe, Ni, Cr (10^{15} cm^{-2})
0
5
10
0
5
10
POSITION ($r-r_\ell$) (cm)